Power Efficient MIMO Techniques for 3GPP LTE and Beyond

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Abstract: **Environmental issues and the need to reduce energy consumption for lowering operating costs have pushed power efficiency to become one of the major issues of current research in the field of wireless networks. The objective of the Green Radio research programme (Core 5) of Mobile VCE is to deliver reduced power consumption of radio access networks. This paper attempts to show that an efficient exploitation of multiple antenna techniques and multiuser diversity in both the time, frequency as well as the space domain can significantly ease the power requirements of a base station, whilst maintaining the same levels of service. Different MIMO transmission and precoding schemes proposed for LTE, achieving varying degrees of multiuser diversity are examined.**

I. INTRODUCTION

There are currently 4 billion mobile phone users in the world. The energy consumption and carbon dioxide emission has become a major concern for wireless network industries as the number of mobile phone users increases. The Mobile VCE 2020 Vision documents states that a typical 24-hour mobile phone network in the UK consumes approximately 40 MW, excluding the power consumed by the users' handsets [1]. The worldwide telecommunication industry is currently responsible for 183 million tones or 0.7% of carbon dioxide emissions, which are increasing at a rapid rate [2]. In addition, the increased energy prices increase the operating cost of cellular systems. In order to develop more power efficient and environmental friendly wireless networks, the Core 5 research programme of Mobile VCE is set to focus on the Green Radio concept. It aims to deliver high data rate services with a 100-fold reduction in power consumption over current wireless communication networks, thereby reducing CO2 emissions and operating costs without compromising (and preferably improving) the Quality of Service (QoS) for user. Architecture and technique are the two complimentary domains in this programme and the latter one is of particular interest to this paper.

LTE is a next major step in mobile radio communications, and will be introduced as Release 8 in the 3rd Generation Partnership Project (3GPP) [3]. The new evolution aims to reduce the delays, improve spectrum flexibility and further reduce the cost for operators and end users. Some of the targets of the standard include a peak download rates of up to 326.4 Mbps for 4x4 antennas and 172.8 Mbps for 2x2 antennas for every 20 MHz of spectrum. In the uplink, a peak upload rate of 86.4 Mbps is expected. Instead of the fixed spectrum in the previous releases, LTE aims to support a scalable bandwidth from 1.25MHz up to 20MHz.

The objective of this paper is to investigate the capabilities of various multiple antenna transmission and precoding techniques in combination with multiuser diversity to reduce the total power consumption needed for a wireless system operation and improve energy efficiency. The use of the MIMO transmission techniques can significantly improve the system performance, reliability or both. One of the popular MIMO techniques is space-time block coding (STBC) which is able to achieve full transmit diversity and enable reliable communication. Thus in LTE, an Alamouti [4][5] based Space-Frequency Block Coding (SFBC) technique is proposed in the standard and it will be considered in this paper. Another technique that is also proposed in the LTE standard is spatial multiplexing (SM) which aims to increase the ultimate spectral efficiency.

A number of MIMO precoding techniques, which can be potentially applied to LTE, are examined in terms of their combined spectral and power saving efficiency. Random Beamforming (RB), widely examined in [4][7][8][9] has shown capabilities in achieving spatial multiuser diversity gain and spatial multiplexing (SM) gain. With much lower feedback requirement than the conventional eigenbeamforming, the transmitter applies a random precoding matrix to the transmitted signal and selects the best user only based on effective SNR (ESNR) feedback indicating channel quality. By using a linear receiver to separate the MIMO spatial layers, allowing allocation of layers of the same slot to different users, an additional 'layer' multiuser diversity gain is extracted, enabling what is called Layered Random Beamforming (LRB).

Recently, an alternative MIMO scheduling and precoding method has been proposed for the Long Term Evolution (LTE) of 3G systems [10], that incorporates an improved interface between the Physical (PHY) and the Data Link Control (DLC) layers in order to provide increased support for on demand quality of service (QoS) [11]. In [12], a precoding method for a MIMO-OFDMA scheme has been proposed in accordance to the LTE standard [10]. This precoding method relies on the use of a known (by both base station and mobile) codebook of unitary matrices, which is determined offline, generated according to a Fourier basis that provides uniform coverage across a sector.

The remaining of this paper is organised as follows: Section II introduces the system and channel model parameters. Section III provides a brief description of the considered MIMO transmission and precoding schemes. Section IV presents theoretical analysis of the capabilities of considered schemes to maintain QoS under different average SNR conditions. Simulation results are presented in section V. Section VI discusses the implications of resource allocation to the BS power consumption based on the analysis of preceding sections. This paper concludes in section VII.

II. SYSTEM AND CHANNEL MODEL

The performance analysis is performed on the downlink of a 3GPP LTE Orthogonal Frequency Division Multiple Access (OFDMA) system. The total system bandwidth is divided into sub-channels, denoted as physical resource blocks (PRBs),

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which are then allocated to different users for multiple access purposes. The key parameters of the considered LTE OFDMA downlink system are given in Table 1. There are 50 PRBs in the 10MHz system, each consisting of 12 adjacent sub-carriers. Instead of feeding back the channel quality indicators (CQI) for all the sub-carriers, a single CQI (calculated from the average quality of the 12 sub-carriers) can be fed back for each PRB and is assumed to be perfectly known at the BS. Perfect channel estimation is also assumed. A 24 bits Cyclic Redundancy Check (CRC) enables error detection at the receiver. Due to the increased computational complexity and the insignificant gain of power control in the frequency domain dynamic allocation, equal power allocation is assumed throughout the simulation.

The channel model used in the simulation is the Spatial Channel Model Extension [13] (SCME) Urban Macro scenario which is specified in 3GPP [14]. SCME provides a reduced variability tapped delay-line model which is well suited for link level as well as system level simulation. A low spatially correlated channel is assumed for all the users where 10λ spacing at the BS is employed. In the simulation, a channel remains the same during a packet transmission. 2000 independently and identically distributed (i.i.d.) channel realisations are considered in each simulation. Six modulation and coding schemes (MCS) levels are considered, as shown in Table 2.

A 2x2 MIMO architecture is considered in this paper but the analysis is readily extendible to higher MIMO orders. Equal power is allocated to each transmit antenna.

Table 1: Parameters for LTE OFDMA downlink

Transmission Bandwidth		10 MHz
Time Slot/Sub-frame duration		0.5ms/1ms
Sub-carrier spacing		15kHz
Sampling frequency		15.36MHz (4x3.84MHz)
FFT size		1024
Number of occupied sub-carriers		601
Number of OFDM symbols per time slot (Short/Long CP)		7/6
CP length (μs/samples)	Short	(4.69/72)x6 (5.21/80)x1
	Long	(16.67/256)

Table 2: Modulation and Coding Schemes

Mode	Modulation	Cod. Rate	Data bits per time slot (1x1), (2x2)	Bit Rate (Mbps)
1	QPSK	1/2	4000/7600	8/15.2
2	QPSK	3/4	6000/11400	12/22.8
3	16 QAM	1/2	8000/15200	16/30.4
4	16 QAM	3/4	12000/22800	24/45.6
5	64 QAM	1/2	12000/22800	24/45.6
6	64 QAM	3/4	18000/34200	36/68.4

III. DESCRIPTION OF INVESTIGATED SCHEMES

A. Random Beamforming and Layered Random Beamforming

With low feedback requirement, random beamforming is considered as a sub-optimal scheme to [4]. A unitary matrix V_r is generated from the random channel matrix H_r and it is applied to the sub-carriers of the OFDMA signal on a PRB basis. The received signal after FFT and guard interval removal becomes (time index t is omitted):

$$\begin{aligned} Y_{k,s} &= H_{k,s}V_{r,s}X_s + N_{k,s} \\ &= U_{k,s}D_{k,s}\left(V_{k,s}\right)^H V_{r,s}X_s + N_{k,s} \end{aligned} \tag{1}$$

where k denotes a user index, s denotes a sub-carrier index, $(.)^H$ denotes the Hermitian function and $H_{k,s}$ is a matrix containing user k 's frequency responses of the channels between N_t transmit and N_r receive antennas at sub-carrier s. $D_{k,s}$ is a diagonal matrix including all the singular values of $H_{k,s}$ and $U_{k,s}$ and $V_{k,s}$ are the unitary matrices obtained by applying Singular Value Decomposition (SVD) to $H_{k,s}$. X_s denotes an $N_t \times 1$ matrix containing the transmit signals at sub-carrier s at the BS and $N_{k,s}$ represents the additive complex Gaussian noise with zero mean and variance $\left(\sigma_{k,s}\right)^2$. If V_r is equal to V_k, the $V_k^H V_r$ term becomes an identity matrix and the user k is said to be in the true beamforming configuration.

The system adopts a linear MMSE receiver, which has interference suppression capability. For a 2x2 MIMO system, the MIMO channels can be decomposed into 2 separate spatial layers, which can be allocated to either one user for the RB scheme or to different user(s) for the LRB case. The received signal $Y_{k,s}$ is multiplied by the MMSE filter $G_{k,s}$:

$$G_{k,s} = \left(\left(H_{k,s}V_{r,s}\right)^H \left(H_{k,s}V_{r,s}\right) + SNR^{-1}I\right)^{-1} \left(H_{k,s}V_{r,s}\right)^H \tag{2}$$

For data stream q at sub-carrier s, the user k computes the $ESINR$:

$$ESINR_{k,s}^q = \frac{E_s}{\left|\left(A_{k,s}\right)_{qq}\right| \sigma_{k,s}^2} - 1 \tag{3}$$

where $A_{k,s} = \left(\left(H_{k,s}V_{r,s}\right)^H \left(H_{k,s}V_{r,s}\right) + SNR^{-1}I\right)^{-1}$. E_s denotes the average symbol energy and $(\cdot)_{qj}$ indicates the element located in row q and column j.

Every user calculates the average data rate across all sub-carriers in each PRB and sends it to the BS through the feedback channel. For PRB c, if the index of the starting sub-carrier is n and finishing sub-carrier is m, the average rate of user k is given by [8]:

$$R_{k,c} = \frac{1}{m-n+1} \sum_{s=n}^{m} \sum_{q=1}^{N_r} \log_2\left(1 + ESINR_{k,s}^q\right) \tag{4}$$

The BS allocates each PRB to the user having the highest rate. In the case of SISO, the resource allocation is based on the channel gain, where the detailed description is well known and hence omitted here due to limited space.

For the LRB scheme, the different spatial layer can be allocated to a different user to achieve an additional spatial multiuser diversity gain. However, it increases the feedback by the number of spatial layers (minimum number of transmit and receive antennas) compared to the RB scheme.

Based on the $ESINR$ calculated using equation (3), the user k calculates the rate of each spatial layer on a PRB basis [8]:

$$R_{k,c}^q = \frac{1}{m-n+1} \sum_{s=n}^{m} \log_2\left(1 + ESINR_{k,s}^q\right) \tag{5}$$

For every PRB, the BS allocates each spatial layer to the user whose channel conditions of the corresponding layer are best.

C. Unitary Codebook based Beamforming

Unlike the random unitary matrix generation, proposed for RB and LRB systems, unitary codebook based beamforming suggests that a predefined set of antenna beams is to be determined offline, which altogether ensure a good sector coverage [11]. The proposed pre-coder design relies on the

Fourier basis for ensuring uniform sector coverage. The codebook E, consists of the unitary matrix set, i.e. $V_E = \left\{ V_E^{(0)} \ \dots \ V_E^{(G-1)} \right\}$, where $V_E^{(g)} = \left\lfloor v_{E,0}^{(g)} \ \dots v_{E,M-1}^{(g)} \right\rfloor$ is the g-th precoding matrix, and $v_m^{(g)}$ is the m-th precoding vector in the set. According to the Fourier basis,

$$v_m^{(g)} = \frac{1}{\sqrt{M}} \left[w_{0m}^{(g)} \ \dots \ w_{(M-1)m}^{(g)} \right]^{\mathrm{T}}$$
$$w_{nm}^{(g)} = \exp\left\{ j \frac{2\pi n}{M} \left(m + \frac{g}{G} \right) \right\} \tag{6}$$

Similarly to the RB approach, unitary codebook based beamforming defines two modes of operation, depending on the spatial resource allocation process. Single user MIMO (SU-MIMO) systems, assign both spatial streams to the same user, realising Spatial Division Multiplexing (SDM). A more efficient spectrum utilisation can be achieved via Multi-user MIMO (MU-MIMO), whereby the spatial dimension is exploited, in a similar fashion to LRB. MU-MIMO can also be known as Spatial Division Multiple Access (SDMA) and is expected to achieve a greater overall system performance gain. In a full feedback scheme, the serving BS receives CQI information regarding the spatial layers from all unitary matrices, allowing an overall optimisation of the aggregate rate by selecting the matrix that achieves the overall highest spectral efficiency. Similarly to RB and LRB, every user calculates the average data rate across all the sub-carriers in each PRB and sends it to the BS through the feedback channel. The average data rate for the PRBs can be calculated using the equations 4-6 except that the Fourier based unitary matrices are used.

Depending on the codebook size G, unitary codebook based beamforming imposes the additional feedback requirement of transmitting a total number of G CQI values along with the corresponding matrix index for each CQI. In order to reduce this uplink feedback overhead, partial feedback techniques have been proposed in [12], whereby each user feeds back CQI for only its preferred matrix. In [15] it was shown that partial feedback SU-MIMO techniques attain the same performance as full feedback schemes. For MU-MIMO schemes the degree of partial feedback performance convergence to full feedback is dependent on the combination of the number of users and the codebook size G.

Subsequent sections will assume a range of users from 1-25 and a fixed codebook size G=2. Table 3 presents the uplink feedback overhead associated with each of the precoding schemes investigated in this paper. Perfect feedback information is assumed in the simulation. However in practise, the feedback information is quantized to reduce the amount of feedback overhead in the uplink. In LTE, it is proposed that 5 bits are used to represent each CQI [16], with only very marginal performance degradation. Note that in the proposed LTE system, SFBC is not considered in combination with multi-user diversity and therefore it does not require channel feedback.

IV. THEORETICAL ANALYSIS

The benefits of multiuser diversity (MUD), whereby users are scheduled only on their strongest PRBs have been widely studied in literature e.g. [17][18]. Provided that different users experience independent fading, the average system spectral efficiency can be increased as a function of the number of users. The precoding systems examined in this paper achieve varying degrees of multiuser diversity. It is therefore expected that for a given SNR value, different schemes will achieve different spectral efficiency. To illustrate this, Figure 1 presents theoretical spectral efficiency results, calculated according to Shannon's Capacity limit, for a range of SNR values for a total number of users, K=10, for the MIMO precoding schemes outlined in the previous section. SISO capacity is also included for reference. The schemes that achieve the highest degree of MUD exploitation (time/frequency and space) e.g. MU-MIMO and LRB achieve the highest capacity for any given SNR value.

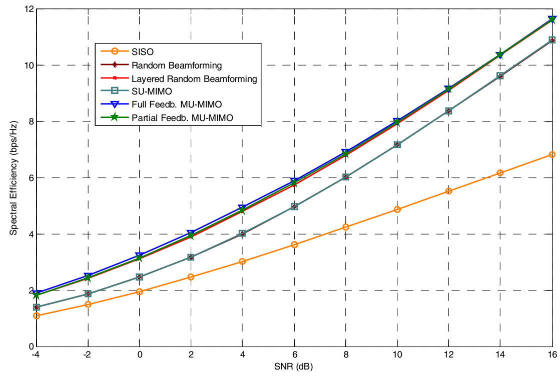

Figure 1: Theoretical Spectral Efficiency for SISO and Different Precoding Schemes for K =10

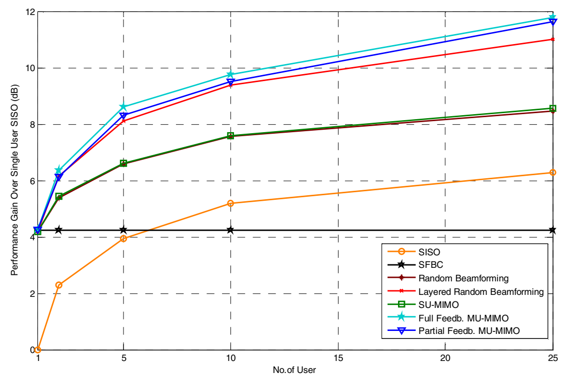

Figure 2: Theoretical Results of Performance Gain of Multiuser SISO and other MIMO Precoding Schemes over Single User SISO Scenario

Figure 2 shows the theoretical results of the performance gain of multiuser SISO and other MIMO precoding schemes over single user SISO scenario, as a function of the number of users at a fixed spectral efficiency of 3bps/Hz. The fixed spectral efficiency of 3bps/Hz is a fairly arbitrary metric. It is expected that similar trends will occur for other spectral efficiencies, but with a change in the absolute SNRs values. A trend, whereby the performance gain increases as a function of the number of users is observed. It is worth to note that resource allocation is not considered in the case of SFBC scheme. This is consistent to the proposed LTE standard where channel dependent scheduling is not applicable to the SFBC scheme [5]. A notable difference between schemes utilising the additional spatial diversity component and those who do not can be observed.

The performance gain over the single user SISO scenario can be translated into a power saving at the BS. Theoretical results show that depending on the degree of MUD exploitation, transmit power from the BS could be significantly reduced, whilst attaining the same average service levels.

V. SIMULATION RESULTS

Figure 3 shows the simulated performance of spectral efficiency of SISO scheme and different MIMO precoding schemes in the downlink of 3GPP LTE. The spectral efficiency is derived from the achievable average throughput of all the users given the transmission bandwidth. The achievable average throughput is given by, *Throughput = R(1-PER)* where R and PER are the bit rate and the residual packet error rate for a specific mode respectively. The throughput envelope is obtained by using ideal adaptive modulation and coding (AMC) based on the (throughput) optimum switching point. Simulated results are very consistent with the theoretical results. The simulation results show that the spectral efficiency of MIMO precoding schemes significantly outperform the SISO scheme. Besides that, in line with the theoretical results the additional spatial diversity of both MU-MIMO schemes and LRB scheme achieve a further performance gain of 2-3dB compared to SU-MIMO and RB schemes.

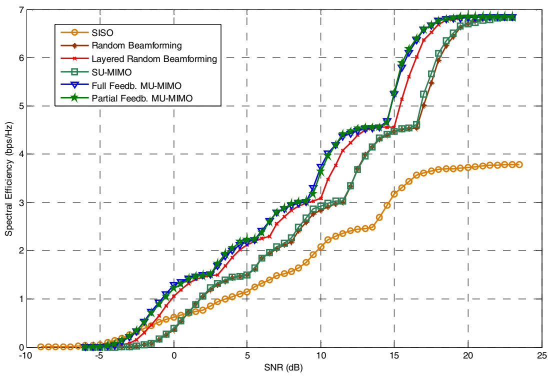

Figure 3: Simulated Spectral Efficiency for SISO and Different Precoding Schemes for K =10

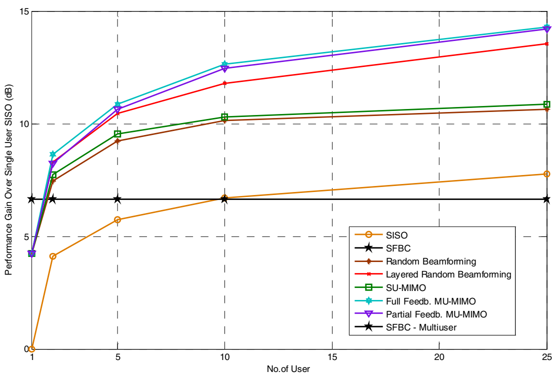

Figure 4: Simulated Performance Gain of Multiuser SISO and other MIMO Precoding Schemes over Single User SISO Scenario

Figure 4 shows the simulated results of the performance gain of multiuser SISO and other MIMO precoding schemes over a single user SISO scenario, as a function of the number of users at a fixed spectral efficiency of 3bps/Hz. The simulated results match with the theoretical trend of Figure 2. Figure 4 shows that a significant gain is obtained by exploiting multiuser diversity, accounting to 7-8dB of the power gain. This can be clearly observed in the SISO scenario, where in this case, the performance gain comes solely from the MUD gain. In addition to that, more gain can be achieved by using MIMO transmission techniques such as SFBC and SM. Furthermore, considerable gain can be achieved by both MU-MIMO schemes and LRB where additional spatial diversity is exploited. The use of precoding matrices can optimise the perceived gain in the receiver to achieve the additional gain. It has to be noted that results of Figure 4 are specific to the specific scenario (3bps/Hz and K=10). Granularities in the PHY mode selection and the different SNR ranges that arise from simulation result in different modes being selected from different precoding schemes, which explain the deviation of the performance gains from theoretical to simulation results. It is worth noting however, that by using AMC, actual simulation results can outperform theoretical expectations.

VI. DISCUSSION

The power efficiency of a given scheme can be associated with a cost metric, $\sum_{k=1}^{K} P_k / R_k$, with a corresponding Jain's power fairness index (PFI) . The PFI is defined as:

$$PFI = \left(\sum_{l=1}^{K} \frac{P_k}{R_k}\right)^2 \Big/ K\sum_{k=1}^{K}\left(\frac{P_k}{R_k}\right)^2 \qquad (7)$$

This cost metric can be considered as the aggregate power required for achieving a specified spectral efficiency. The lower the cost metric the higher the power efficiency is. A tradeoff is known to exist between power efficiency and fairness. Analysis in section IV and V, has shown that precoding schemes that harness the benefits of multiuser diversity to a higher degree require less transmit power from the BS to achieve the same throughput. It is thus expected that these schemes will have a lower power utility, which translates improved power efficiency.

In Table 4 the cost function and the corresponding variance over different channel realisations is presented. These results are in accordance with Figures 2 and 4, showing that schemes employing a higher degree of diversity achieve the lowest cost in terms of power for providing a fixed amount of bits. It can also be observed that a more equally distributed cost function is obtained from the more power efficient schemes. Hence, a higher degree of multiuser diversity not only ensures an overall improvement in power efficiency but also improves the reliability of the cost estimation. This improved reliability can be attributed to the fact that deep fades occurring in wireless channels are effectively removed from the aggregate received channel signal at the BS [17]. Schemes exploiting the additional spatial layer for diversity generate a more flat aggregate channel, resulting in fewer deep fades and hence in a more predictable channel response.

Table 4: Average and Variance of the cost metric for Different Precoding Schemes

	Cost Metric	Variance
SISO	2.1593	0.6923
Random Beamforming	0.9171	0.0573
Layered Random Beamforming	0.8699	0.0214
SU-MIMO	0.9172	0.0575
Full Feedb. MU-MIMO	0.8536	0.0285
Partial Feedb. MU-MIMO	0.8602	0.312

The PFI provides an indication of how fairly power is allocated to different users with respect to their achieved rates. Figure 5 shows the cumulative distribution functions of the PFI, measured over a number of channel realisations. A PFI value close to unity indicates a high degree of fairness. Schemes utilising the additional spatial layer, e.g. LRB and

MU-MIMO (full feedb. and partial feedb.) achieve an overall higher power allocation fairness, with PFI values consistently closer to unity.

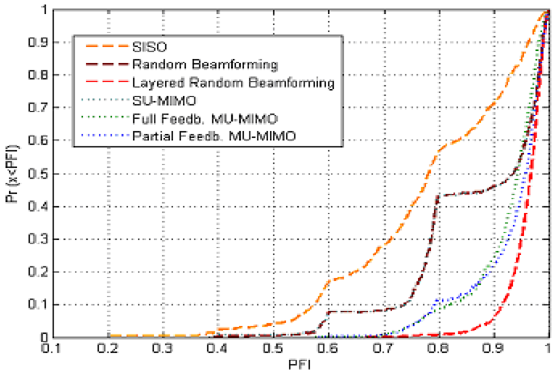

Figure 5: Power Fairness Index for SISO and Different Precoding Schemes

VII. CONCLUSIONS

The concept of green radio is to develop environmental friendly, low-power and energy efficient solutions for future wireless networks. This paper investigates the power efficiency of a number of MIMO transmission and precoding techniques, SFBC, RB, LRB, SU-MIMO, and MU-MIMO with full and partial feedback. The analysis is performed on the downlink of a 3GPP LTE OFDMA system and both numerical and simulation performances are presented. A detailed feedback overhead of different MIMO schemes is presented. In addition, the power efficiency of the overall system and individual users are also discussed and compared for different MIMO precoding strategies. For the proposed LTE system, if no multi-user diversity is considered, SFBC is a feedback free MIMO transmission scheme and achieves significant power saving over a SISO system. However, since it does not offer data rate improvement, the savings on cost per bit is still limited. The capabilities of these MIMO precoding strategies to exploit multiuser diversity in time, frequency and space domain varies. It is observed that increasing multiuser diversity significantly improves the power efficiency. All MIMO schemes benefit from multiuser diversity and show improved power efficiency as the number of users increases. The MU-MIMO and LRB are the most power efficient and fair schemes as a result of an additional layer spatial multiuser diversity gain, although they have a larger feedback overhead. Between MU-MIMO and LRB, MU-MIMO outperforms LRB in terms of overall power efficiency and therefore it is the most power cost efficient scheme.

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Table 3: Feedback overhead for various MIMO schemes for G=2 and M=2

	Preferred Layer 1 CQI	Preferred Layer 2 CQI	Alternative Layer 1 CQI	Alternative Layer 2 CQI	Preferred Matrix Index	Total bits per PRB
SISO	5bits				-	5 bits
SFBC	N/A (No MUD is considered)				-	N/A
RB	5 bits				-	5bits
LRB	5bits		5bits		-	10bits
SU-MIMO	5 bits		5 bits		2 bits	12 bits
Full Feedb. MU-MIMO	5 bits	5 bits	5 bits	5 bits	2 bits	22 bits
Partial Feedb. MU-MIMO	5 bits	5 bits	-	-	2 bits	12 bits